

The Electron Beam Scanlaser: Theoretical and Operational Studies*

Abstract: This paper presents the theory, design, and initially observed operating parameters of the Electron Beam Scanlaser, a scanning laser device in which a modified electro-optic display tube selects one of many degenerate transverse modes of a flat-field conjugate resonator. The version considered uses a KDP crystal in the mode selector and an ionized mercury hollow cathode discharge as active element. Some observations reported are resolution (10 lines/mm); sweep rate (100 μ sec/line); light decay time (2 msec, minimum); and power/spot (1W pulsed.) Laser output power is about 30 dB greater than electron beam power.

1. Introduction

Demonstration of the first laser opened a wide area of problems to the field that has since become known as Quantum Electronics and, in addition, reawakened interest in several "classical" problems in optics. Two of these, *light modulation* and *light deflection*, are of paramount importance because of the great possibilities inherent in their application. The problem of light modulation, which is the key to optical communications systems, is nearly solved, and practical devices and systems have been demonstrated by many groups.¹ Light deflection, however, is no easy task, since the physical phenomena which are suitable for modulation of light are barely large enough to produce practical deflection.

Nonetheless, light deflection has been demonstrated with a variety of devices, among which are electro-optic prisms,² mechanically or piezoelectrically driven mirrors,³ mechanical or electro-optical shutters,⁴ incoherent arrays,⁵ and acoustic or electro-optic gratings.⁶ These devices all fulfill various needs with respect to scanned light beams, but they also have the common property that they treat the laser as a simple source of collimated and monochromatic light and take no advantage of its nonlinear properties.

It is our purpose to describe here a light-scanning device, the electron-beam scanlaser, which does capitalize on the nonlinear properties of the laser. In the scanlaser, however, laser light is not actually "deflected"; instead, the laser it employs is so controlled as to emit only from one desired point on the output mirror at any given time.⁷ More explicitly, a scanlaser is a laser device consisting of an optical

resonator capable of supporting a large number of transverse modes, and of an electrical means for selecting those modes that are to lase at specified times. Thus, the two vital parts of a scanlaser are its special *multimode cavity* or resonator, and its *mode selector*.

To be useful for a scanlaser, a resonator must satisfy stringent requirements. First, it must support a large number of transverse modes, and the *Q*'s of these modes must be equal or very nearly so; i.e., the resonator must be highly degenerate. Second, at least one possible set of such degenerate modes must be spatially distinct so that convenient and precise spatial mode selection is possible. Third, to achieve maximum economy of utilization of the active lasing medium, it is required that, ideally, all modes use the same active volume so that no inverted population is unused at any time. In order that the mode selector be precise, fast, and economical, it must utilize as little control energy as possible. The principle of operating within the laser makes this feasible, as only small amounts of loss are required to shift a laser from its non-oscillating to its oscillating state, resulting in a large change in light output.

In subsequent sections of this paper we will describe in detail the construction and observed properties of the electron-beam scanlaser as one important physical embodiment of the concepts discussed above. The paper will open with a discussion of the concept of a degenerate resonator, and of the particular degenerate resonator used, the flat-field conjugate resonator. This will be followed by a description and analysis of the electron beam mode selector. Finally, we will then describe a working model of the electron-beam scanlaser and report on its properties.

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2. Conjugate resonators

All optical resonators are essentially multimode resonators simply because their dimensions are large multiples of the radiating wavelength. Thus, in the field of lasers one usually faces the problem of how to reduce a large number of available modes to one or a few into which the inverted population of the lasing medium may be channeled to produce coherent radiation.

In the present application the problem was different: we wanted a laser resonator that would be capable of lasing in a large number of transverse modes so that one of them could be selected at a time. It might appear, from what was said above, that this need could be satisfied in a trivial manner. For example, one would only have to increase the diameter of a Fabry-Perot cavity and thereby increase its Fresnel number and through it the number of available transverse modes. However, it turns out that sheer "multimodedness" is not enough. In addition, it would be most convenient to have a resonator whose multiple transverse modes are mutually degenerate, i.e., a set of modes, every one of which would require the same loss to be spoiled or the same amount of gain to be made to lase.

Further, for obvious reasons of economy, one would require that all of these modes share the same inverted population so that no portion of the active medium is pumped in vain. (If this were not the case, one could simply use a large number of distinct lasers). Finally, for the mode selector to be a point-by-point device, the modes would have to be positionally non-overlapping, i.e. they would have to be focused in the plane where mode selection takes place.

The family of resonators that evolved on the basis of the above requirements is referred to as (optically) conjugate resonators, where the word "conjugate" implies that their reflective surfaces are optically connected in such a manner that they are imaged on one another. In other words, a conjugate resonator is an imaging system in which the object and the image planes (or surfaces) are mirrors. It will be seen that such resonators satisfy most of the requirements cited earlier.

The first such resonator, the Conjugate Concentric (CC) resonator, was described in an earlier paper,⁸ and is schematically shown in Fig. 1. This resonator uses a solid state laser medium, which in addition to supplying optical gain, serves also as an image forming element—a lens.

It is easily seen that this resonator is of multimode character and that its modes could be highly degenerate. The number of transverse modes depends only on its Fresnel number $N = ab/\lambda R$ (see Fig. 1, where the diameter of the narrow portion of the active lens is $2a$, and that of the mirror is $2b$) and the degeneracy of these modes is apparent from the spherical symmetry of the resonator. The mode shown in the figure is only one of the many similar modes that are possible in such a resonator. It is clear that each traverses the same optical path and, under the assumption

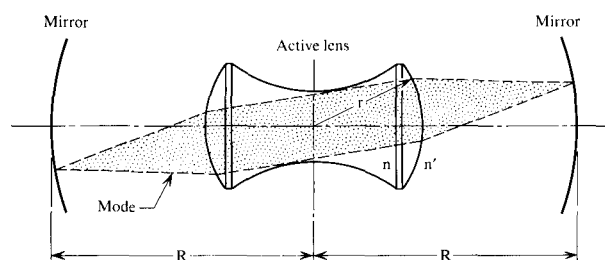
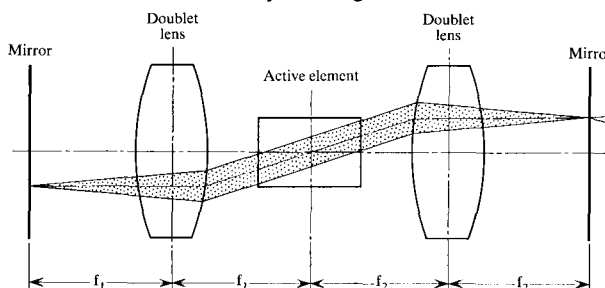


Figure 1 The conjugate concentric cavity.

Figure 2 The flat-field conjugate resonator. The active element is a hollow-cathode mercury discharge.



of uniform inversion within the active medium, acquires the same gain per pass. It is also clear that the requirement for use of the active volume is fairly well satisfied: the modes have a *large common volume*. Also, they are focused at the mirrors and as such are easily distinguishable by any positional mode selector.

The primary difficulty with this resonator was in the spherical shape of the mirror surfaces, for the mode selector to be described later cannot be easily fitted into a spherical geometry. Furthermore, the CC resonator is intrinsically unsuited for gaseous active media.

The above-mentioned shortcomings of the CC resonator can be overcome by the optically equivalent Flat Field Conjugate (FFC) resonator.⁹ In it the lenticular action may be divorced from the active medium and provided by separate lenses. Most important, these lenses are so chosen and so positioned that the degeneracy is now achieved over a planar or flat optical field. Such a resonator is illustrated in Fig. 2. The mirrors are in the focal planes of the two lenses, and the lenses themselves are separated by the sum of their focal lengths, such that the two mirror planes are related to the symmetry plane—or vice-versa—by the Fourier transform relationship. A typical mode of such a system is also shown in Fig. 2. One should note that under these conditions the chief ray of each mode terminates perpendicularly to each of the two planar mirrors. Evidently, the active medium can now be either in the solid or gaseous state.

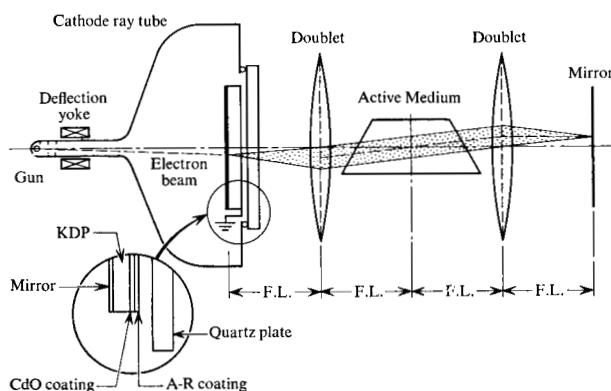


Figure 3 The electron-beam scanlaser. The active element is a hollow-cathode mercury discharge.

The integral equation for the eigenmodes of the FFC resonator is equivalent to that for those of the CC resonator (assuming ideal lenses), and this has been discussed in detail previously.⁸ The relevant conclusions of that study can be summarized by saying that the "conjugate" resonator does support a multiplicity of degenerate modes, and these have the shape of the well-known prolate spheroidal wave functions.¹⁰

3. Mode selection

By mode selection we mean, in this context, a process of selecting one transverse mode at a time and suppressing all others via some electronically controlled device. Clearly, the suppression of unwanted modes can occur only by the insertion of sufficient losses for the unwanted modes. Since the modes in a conjugate resonator are resolvable by both their direction and the transverse position of their foci, the mode selectors can, in principle, be either directional or positional. Up to now we have successfully developed only positional mode selectors, and the remaining discussion will be devoted to them exclusively.

Although, in principle, any effect or mechanism that is able to rapidly introduce a loss into the cavity under some external electrical control is then a candidate for a mode selector, we limit ourselves here to the effect used in the scanlaser. It is the linear electro-optic (Pockels) effect, which introduces a certain amount of birefringence into the path of the linearly polarized laser light, which is then converted into an increased or decreased feed-back for one or a group of transverse modes of the resonator. One Kerr effect mode selector, referred to as a Kerr-Babinet filter, has been described elsewhere.¹¹

In the *electron-beam scanlaser*, as the name implies, the electro-optic mode selector works in conjunction with an electron beam, the form being that of a modified electro-optic display tube.¹² This type of selector is capable of high spatial scanning capacity and relatively fast switching speed,

and is well-suited for operation in the FFC resonator, as shown in Fig. 3. Operation of the selector is straightforward. A polarized laser beam is obtained, either by means of a polarizing sheet or prism within the resonator, or by Brewster angle windows on the discharge tube, or by natural polarization in the active medium. The Q is then spoiled over the full field by means of a plate which has a uniform birefringence B_0 . This plate converts the linearly polarized output of the active medium to an elliptically polarized beam. Thus, the reflected beam, when passed back through the polarizer (acting now as analyzer) will be attenuated, thereby lowering the Q of the resonator. The electron beam, in conjunction with the electro-optic medium, acts to *locally raise the Q* by inducing birefringence of the opposite sign, and thus selects a certain mode or set of modes which are alone able to oscillate.

In detail, then, we note that the charge deposited on the dielectric mirror by the electron beam produces an electric field across the crystal, terminating in the grounded transparent electrode. This field is along the z -axis of the (for example) z -cut crystal of KDP. The birefringence B thereby induced, opposite in sign to that of B_0 , leads to a fractional cavity loss γ given by the expression

$$\gamma = \gamma_0 + \beta \sin^2 (B - B_0), \quad (1)$$

where γ_0 is the (fixed) insertion loss including mirror transmission, and corresponds to the optimum operating point of the scanlaser, and where β is the extinction factor of the polarizers. B and B_0 are both measured in radians. Since the induced birefringence is a function of position so, too, is the loss.

Evidently, in the region for which $B = B_0$, the cavity loss will be a minimum (equal to γ_0), and those modes which are focused in this area will come into oscillation. The size of the lasing area and, therefore, the resolution of the mode selector, will depend on the number of modes that have been made to lase, and that number will, in turn, depend on the amount of excess loss the laser can tolerate, as well as on the size of the region for which $B = B_0$. This region depends on the size of and charge distribution in the electron beam focus, and on the thickness and electro-optic properties of the crystal. The following analysis shows in detail what the spot size will be for a particular, somewhat idealized situation.

We will assume that the charge has been deposited on the dielectric mirror surface in the form of a uniformly charged disc of radius a . We will also assume that the light incident on the mirror is a parallel beam; in this case the total birefringence, for light passing through the crystal and reflected back, is given by

$$B(r') = KV_d[q(r')]. \quad (2)$$

That is, the birefringence for a ray a distance r' from the center of the disc depends only on the potential V_d on

the dielectric surface, and this potential is a function of the charge distribution $q(r')$; the constant K is given by $2\pi\epsilon_0\epsilon/\lambda$. Now it is well known that the potential V at the point (r, θ, ϕ) due to a uniformly charged disc with radius a , with density $q/\pi a^2$, and with dielectric constant of the medium ϵ , is given (in mks units) by the following:

$$V(r, \theta) = \frac{q}{2\pi\epsilon a} \left[1 - \left(\frac{r}{a}\right) |P_1(\cos \theta)| + \frac{1}{2} \left(\frac{r}{a}\right)^2 P_2(\cos \theta) - \frac{1}{8} \left(\frac{r}{a}\right)^4 P_4(\cos \theta) + \dots \right]; \quad r < a$$

$$V(r, \theta) = \frac{q}{2\pi\epsilon a} \left[\frac{1}{2} \left(\frac{a}{r}\right) - \frac{1}{8} \left(\frac{a}{r}\right)^3 P_2(\cos \theta) + \frac{1}{16} \left(\frac{a}{r}\right)^5 P_4(\cos \theta) + \dots \right]; \quad r > a \quad (3)$$

which is, of course, independent of ϕ .

Because of the presence of an equipotential surface (i.e., the grounded coating on the opposite face of the crystal), the potential V_d across the crystal is that due to the deposited charge and its image. For the plane of interest, the potential V_1 due to the original charge is $V(r', \pi/2)$. Further, since in practice the thickness of a KDP crystal is necessarily 50 to 100 times larger than the radius of the charge disc (i.e., $d \gg a$), we may assume that the potential V_2 due to the image charge $-q$, $-V(2d, 0)$, is negligible. Then, evaluating Eq. (3) for this special case, we obtain

$$V_d(r') = V(r', \pi/2) - V(2d, 0)$$

$$= \frac{q}{2\pi\epsilon a} \left\{ \left[1 - \frac{1}{4} \left(\frac{r'}{a}\right)^2 - \frac{3}{64} \left(\frac{r'}{a}\right)^4 - \dots \right] \right\}; \quad r' < a$$

$$= \frac{q}{2\pi\epsilon a} \left\{ \left[\frac{1}{2} \left(\frac{a}{r'}\right) + \frac{1}{16} \left(\frac{a}{r'}\right)^3 + \frac{3}{128} \left(\frac{a}{r'}\right)^5 + \dots \right] \right\}; \quad r' > a \quad (4)$$

The resulting potential is plotted in Fig. 4; at the center of the disc the potential has its maximum value $V_0 = q/2\pi\epsilon a$, and drops parabolically to two-thirds of this value at the edge of the disc. Outside the disc the fall-off is more nearly linear with distance. The dashed curve in Fig. 4 shows the modifications to be made when the crystal is thin enough for the excluded terms in Eq. (4) to become significant.

For practical purposes, the potential can be fairly well approximated by a cosine function:

$$V_d(r') \approx (q/2\pi\epsilon a) \cos(\pi r'/4a); \quad |r'| < 2a \quad (5)$$

$$\approx 0; \quad \text{elsewhere.}$$

(It will be noted, of course, that the capacitance implied by Eq. (5) is not that of a simple parallel-plate dielectric-filled capacitor.)

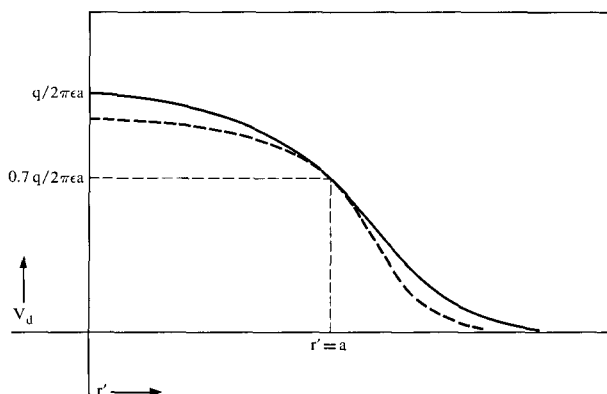
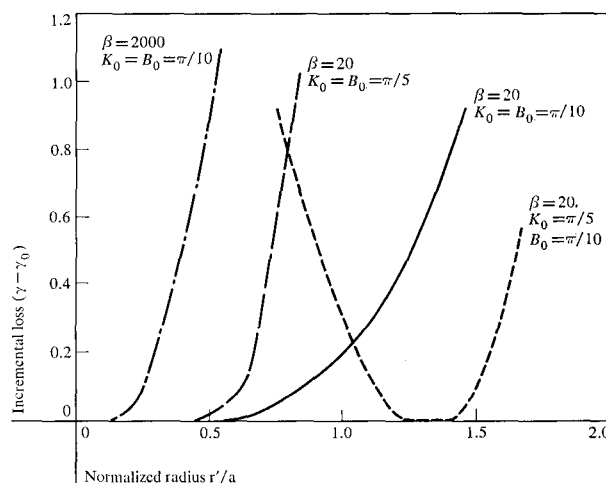


Figure 4 Potential due to a disc of charge.

Figure 5 Relative loss as a function of distance from center of charged disc in the scanlaser. K_0 = maximum charge-induced birefringence; B_0 = bias birefringence; β = extinction ratio of polarizer-analyzer.



The cavity loss, using Eqs. (1) and (2), is seen from the foregoing to be:

$$\gamma = \gamma_0 + \beta \sin^2 [K_0 \cos(\pi r'/4a) - B_0], \quad |r'| < 2a \quad (6)$$

$$= \gamma_0 + \beta \sin^2 B_0, \quad |r'| > 2a$$

where $K_0 = Kq/2\pi\epsilon a$. Values for this expression are plotted in the solid curve of Fig. 5 for the experimentally interesting cases of a tenth-wave bias and an extinction of 20. Several interesting conclusions can be drawn from that curve. First, the fractional loss is 50 percent for r' only $1.3a$; if the bias and current are doubled (as in the dashed curve), the fractional loss becomes 50 percent for $r' = 0.7a$. The functional relations in Eq. (6) are also such that the loss is relatively independent of the extinction ratio, but we have chosen a particularly conservative value (of the sort we expect from

a pair of Brewster angle windows). An extinction ratio of 2000 gives spectacular improvement to the resolution that can be achieved and this is also shown.

It is important at this point to recall that the present analysis assumes a static uniformly charged disc. However, any real electron beam will have a nearly gaussian profile. Thus, the charge distribution itself will fall off as the radius increases, which means that the actual resolution for an electron beam with an "effective" radius a might be substantially better than we have calculated. Experiments further indicate that lateral spreading of the charge has a negligible effect.

Another interesting aspect of the electron beam mode selector is also shown in Fig. 5, where we see the effect of "too much" charge. Clearly, if the charge-induced birefringence is unequal to the bias, the laser will remain below threshold. If, however, the potential is too large near the center of the spot, there will still be an annulus in which the bias is canceled, and the modes selected will be those which fall within the annulus. If the charge is large enough, several rings could, in principle, be observed.

When the charge decays, of course, the laser will be turned off. This in itself has some interesting consequences. For example, in the case of an annular set of modes, the decay of the charge (if we assume it to be through the KDP rather than on the surface) will result in a contraction of the ring. Moreover, if the operating point of the scanlaser is chosen so that the excess gain in the cavity is minimal, then the loss of only a small amount of the charge can extinguish the laser. Thus, we may have a situation in which the charge decay time is much longer than the period during which the laser oscillates.

A final point concerns the turn-on time for a mode. This is limited by the excess gain in the cavity, which is determined by the intrinsic gain of the active medium and the insertion loss of the mode selection elements. For an ion laser in the small-signal case, one can show that the turn-on delay T_D is approximately equal to $5nL/G$ μ sec, where L is the cavity length in meters, G is the excess gain in percent, and n is the refractive index of the cavity medium. Good optical engineering can hold losses to 5 percent, and since it is feasible for an ion laser to have a gain of 25 percent in a 20-cm-long discharge,¹³ the device should readily achieve a 5 MHz sweep rate with existing laser media.

4. Description of the operating device

As we have remarked, the scanlaser comprises two major elements, the resonator and the mode selector. The resonator consists of the active medium and associated optical components, while the mode selector consists of the deflectable electron beam and a KDP sandwich.

The active medium is a hollow-cathode ionized-mercury discharge, as has been described elsewhere.¹⁴ As the mirrors of the resonator, a series of wedged tenth-wave flats have

been used; the reflectivity of the front surfaces varies from 64 to 99.5 percent, depending on the gain of the discharge tube in use.

Theoretically, the best performance is obtained with lenses of the shortest focal length possible for a given discharge tube; however, for a typical field (25-mm-diameter, 200-mm-focal length), almost any lens should be nearly diffraction-limited. In most experiments we have used inexpensive, coated, achromatic doublets with the largest diameters ordinarily available. (Occasionally, simple lenses were also used.) The centering of the lenses is important, and positioning tolerances are of the order of 10 to 20 μ , but the auto-collimation of the lens surfaces is almost irrelevant.

The CRT part of the mode selector is built together with the vacuum assembly so as to form an integral unit. While an ultimate pressure of about 2×10^{-9} Torr can be reached in the entire system, average system pressure is maintained (by an ion pump) at about 3×10^{-7} Torr.

The experimental chamber consists of a stainless steel cylinder, to which are connected the demountable aluminum faceplate assembly and the electron gun. Two commercial electrostatic-focus, magnetic-deflection guns have been used; one is a TV-type gun having a spot size of about 0.4 mm on a Willemite phosphor, and the other is a scan-converter type having an 0.08-mm spot. The KDP crystal is mounted on a copper support which is seated in a Delrin mount and grounded through a microammeter. The faceplate assembly also contains a Willemite glass phosphor plate, mounted behind the KDP, which can be flipped in and out of position when the system is under vacuum for observation and adjustment of the beam. A deflection yoke mounts on the gun in the usual manner, and the electronics for the electron beam are likewise conventional except that the high voltage is on the cathode.

The KDP sandwich consists of the biasing phase plate, which serves also as the vacuum window, and the coated KDP crystal. Apart from the active medium, this forms the heart of the scanlaser and appears to be most in need of further development. The phase plate is a plate of quartz or glass seated in mercury bearings. When a transverse stress is applied to it by means of a pair of sliding wedges, a uniform elasto-optic effect is created over the major portion of the plate.¹⁵ By providing a variable bias, this phase plate allows one to study the operation of the scanlaser in a variety of conditions.

The crystal used is a $25 \times 25 \times 3$ -mm z-cut KDP or deuterated KDP crystal having edges parallel to the a-axes; thus, to obtain proper operation, it must be at an angle of 45° with respect to the edges of the quartz plate. The surfaces of the crystal are flat to a fifth of a wave and parallel to 10 seconds of arc. It is of the utmost importance that scratches be avoided. The surface facing the electron gun carries a multilayer dielectric coating of approximately

Table 1 The scanlaser: Some properties of interest.

	Typical values		Best values	Theoretical values
	Mark I	Mark II		
Spots/field	50×50	250×250	800×800	2000×2000
Spots/second	5×10^4	2.5×10^5	5×10^5	2×10^7
Power/spot (watts)	0.005	0.5	1.0	3.0
Spot decay time (msec)	30	30	1.0	—

99 percent reflectivity at $6150\text{\AA}$ while the other surface is coated with CdO, a transparent conductor (with any resistivity in the range $0.1\text{--}2.0\text{ M}\Omega/\text{square}$). That coating, in turn, is coated with an anti-reflection coating. A 1-mm-wide gold strip around the edge serves as a contact. The transmission of the front surface coatings at $6150\text{\AA}$ is about 90 percent.

5. Device properties

After the electron-beam scanlaser was first operated,¹⁶ a considerable body of performance data was then obtained from work where, because of experimental convenience rather than fundamental limitations, the active medium was a pulsed hollow-cathode mercury laser. Hence, it should be borne in mind that the ensuing discussion of properties pertains specifically to that *pulsed* active medium, and so does not seek to define capabilities to be expected of the scanlaser in a continuous-wave embodiment. Also, since the results reported here (and summarized in Table 1) were obtained with a bench model designed to yield verifiable performance, they will require revision as the system is improved.

• Output parameters

The general mode of scanlaser operation is that of a raster, with both vertical and horizontal blanking turning the electron beam off in between sweeps. Thus far, the shortest interval in which we have written a single horizontal line is $100\text{ }\mu\text{sec}$, done as part of a 6-line raster in which the vertical sweep time was $600\text{ }\mu\text{sec}$. In this case the limitation on writing speed was imposed by the yoke and the deflection amplifiers we used. Thus, $100\text{ }\mu\text{sec}$ does not represent any fundamental limitation.

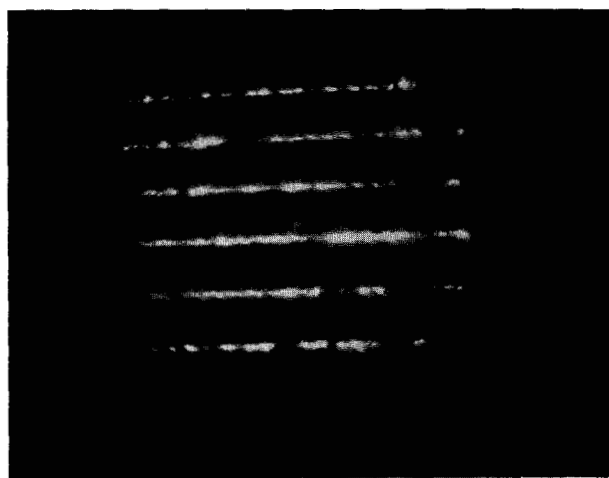
However, to be significant, data pertaining to sweep rate must be accompanied by data concerning resolution. In the accessible field of the scanlaser (a 22-mm-diameter portion of the KDP crystal) we have observed, using a 0.4-mm beam and measuring to the zero point of intensity, a spot as small as 30 microns in diameter. This spot was recorded in the course of a high-speed motion-picture recording of the time development of a single spot (about 300 frames/sec), and its diameter was that of the spot in the first frame for which laser operation was observed. As we did not im-



Figure 6 Blanked horizontal sweep 2 cm long. Note nonuniform spot size. Obtained with low-resolution electron gun; resolution was above 60 spots/line.

mediately turn off the current, however, the 30-micron spot continued to grow. With the same gun and with the beam alternately blanked, we have also swept a single horizontal line which generates a line of spots (Fig. 6). In sweeps like that of Fig. 6 we have observed resolution corresponding to 75 fully resolved spots. Use of the higher-resolution (0.08 mm) gun has allowed us to generate rasters like those shown in Fig. 7 where the (fully resolved) line width of 0.1mm corresponds to more than 220 lines/field.

Although a relatively fast writing rate has been obtained and discussed, the decay time has so far received only passing mention. In KDP and deuterated KDP, the decay times are of the order of milli-seconds—30 msec in KDP and 60 msec or more in deuterated KDP. However, as has been pointed out (see the last paragraphs of Sec. 3), the *light* decay time in the scanlaser is a function of birefringent bias B_0 and is different from the *charge* decay time. This is shown in Fig. 8 for a particular KDP crystal studied in an experiment where the beam current was kept constant while the intracavity losses were varied. It can be seen how the light decay time can be altered; for a deuterated crystal, the fastest light decay time we observed was about 3 msec,



(a)



(b)

Figure 7 High-resolution scanlaser rasters. Current is 10^{-7} A. In (a) vertical sweep speed is 500 msec; horizontal sweep speed, 30 msec. In (b) vertical sweep speed is 50 msec; horizontal sweep speed, 6 msec.

more than 20 times faster than the charge decay time. Using a "doped" crystal of KDP*, we have obtained a *charge* decay time of 2 msec.

Fig. 9 shows results from an experiment aimed at determining the variation of the spot shape as a function of the bias. When the bias is very small, as we have noted earlier, an annular shape results which ultimately becomes a simple dark trace when the bias is zero. The doughnut-shape explains the shape of the curve at the low-loss end; the rounding off that is seen when the loss increases may be simply due to our inability to change the system parameters finely enough.

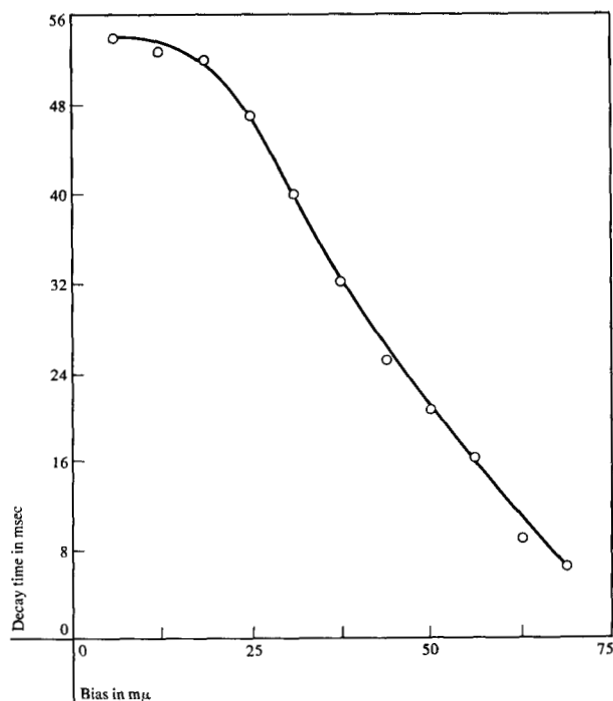


Figure 8 Laser decay time plotted against bias, with constant beam current. A low-resolution electron gun was used.

Little attention has yet been given to the power output of the scanlaser, but the results of a few measurements are of interest. When the device is not operated close to its maximum resolution (but, rather, with a spot size in the order of 0.4 mm), a power output as great as 1 watt per pulse has been observed. This value is about 3 db down from the power that is obtained from the same tube operating into the full field.

• General properties

In addition to the above observations, we have gained considerable information about the general behavior of the operating scanlaser. Theoretical analysis of the conjugate-type resonator predicts that its transverse modes will be related to prolate spheroidal functions, and are, therefore, nearly gaussian in shape. Our experiments have confirmed this prediction.

The longitudinal mode spectrum of the scanlaser is also of interest. Noting that the spectral width of the mercury 202 fluorescence line at $6150 \text{ \AA}$ is only 500 MHz,¹⁷ it will be seen that only a few longitudinal modes can oscillate unless the laser is pumped very hard. In fact, in a cavity 80 cm long, where the mode spacing is 180 MHz, we observed only a single longitudinal mode with a stationary electron beam. However, when the laser is scanning, the optical path is not constant across the field unless specially corrected lenses

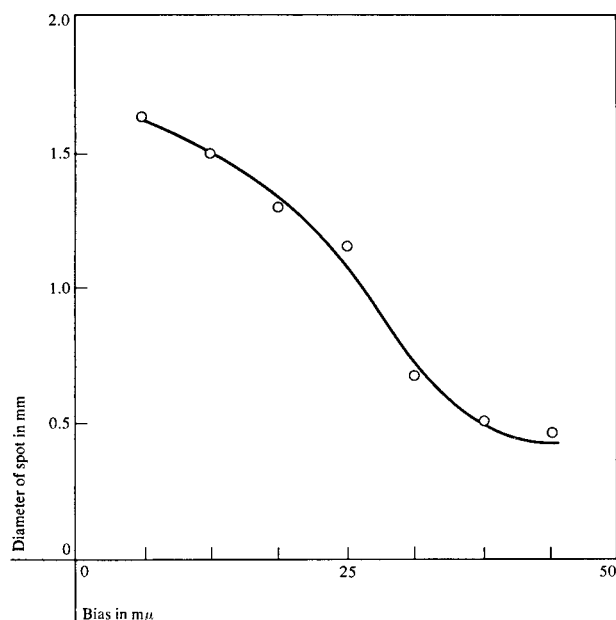


Figure 9 Laser spot size plotted against bias, with constant beam current. A low-resolution electron gun was used; phosphor spot size was 0.9 mm.

are used⁹ and the field is restricted. Consequently, the resonance condition varies and different longitudinal modes appear at different positions. The spot observed with the higher-resolution (0.08 mm) gun is about 0.1 mm in diameter, which would be "diffraction" limited⁸ by a 3-mm aperture. Since it appears that the beam between the lenses has a diameter of only 3 mm, it is likely that the output of the high-resolution scanlaser is fully coherent in both space and time.

In the preceding we have implicitly assumed that the charge is dissipated by ionic conduction directly through the crystal to the ground plane. However, it is reasonable to expect that the surface conductivity along the dielectric mirror may provide significant competition with this mechanism. To determine which of the two mechanisms is dominant, we photographed a spot with a high-speed framing camera running at the rate of 300 frames/sec; with typical laser pulse rates of 500–1000 pulses/sec, this means that, at most, only one laser pulse will be recorded in a single frame. We then operated the scanlaser with a stationary spot which was blanked out twice per second.

The resulting data for the diameter of the spot as a function of time is shown in Fig. 10. It is evident that when the current is turned off, the spot does not spread but, rather, contracts until the annulus (Fig. 11) again becomes a spot, which afterward slowly shrinks in diameter. Thus, we feel safe in concluding that the dominant discharge path is the one through the volume and that the horizontal spread of the charge is negligible.

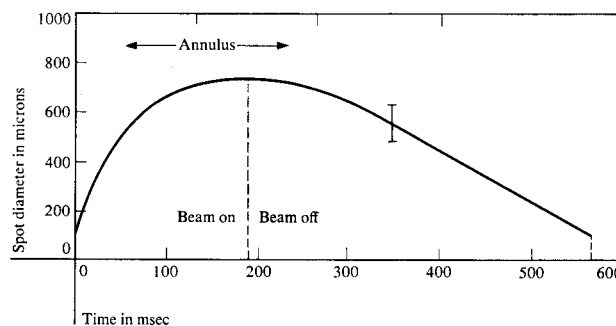
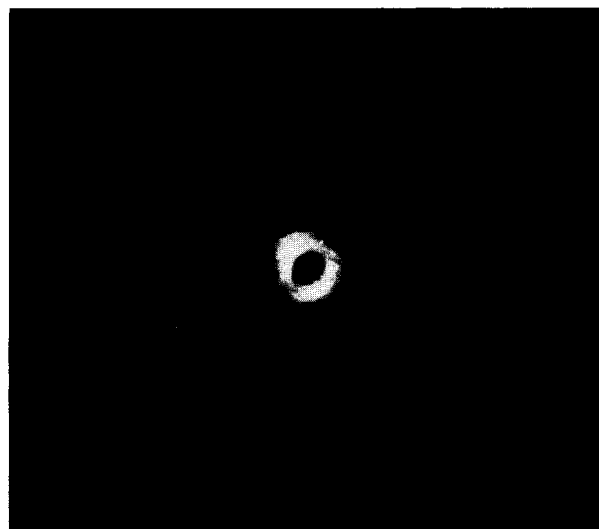


Figure 10 Laser spot size plotted against time. Measurements were taken using Fastax camera recording 300 frames/sec. A low-resolution electron gun was used.

Figure 11 Annular scanlaser spot.



A serious difficulty in the present version of the scanlaser is that the gain, rather than being uniform over the full field, appears to be filtered by some overall fringe structure. As the latter is quite susceptible to vibration and air currents, it must be due in part to optical path variations within the resonator. It is also possible that aspheric lens effects in the active medium contribute to the fringes but we are not yet in a position to be sure.

6. Comparison with the cathode ray tube

As the electron-beam scanlaser is in many ways simply a laser amplifier of electron-beam energy, it will be worthwhile to draw comparisons between it and the CRT. Furthermore, since other laser scanners are still in the early stages of their development, whereas the CRT is the conventional source of a flying spot of light, we find it an appropriate standard for comparison.

Insofar as resolution is concerned, the EBS is clearly capable of writing smaller spots than it would be possible to obtain on a CRT with the same gun. However, in the EBS the ultimate limit on resolution is optical rather than electron-optical. Thus, when compared with a CRT, the EBS can employ electron optics that are far less precise. Moreover, since the registration problems are identical in both schemes, it is implicit that the perfected scanlaser could have a scanning capacity equal to the best CRT.

Insofar as sweep rate is concerned, the scanlaser can perform no better than a CRT. However, the scanlaser requires less beam current (orders of magnitude less) to produce the same light output, so that even here the EBS may very likely be more efficient. The decay time of the present scanlaser is an ambivalent property; for display applications, it is an asset, while for some other applications it might be a liability. However, the possibility of using materials with a faster decay time is ever present, and here the scanlaser offers the flexibility of variable decay time. For example, if the electro-optic medium were also photoconductive (e.g., ZnTe) the decay time could be altered at will by varying the level of ambient illumination. The use of an additional, charge "erasing" gun is another possibility.

As to brightness, power output, and coherence of the output, the EBS potentially exceeds the CRT by a good margin. The fact that milliwatts and watts of light output can be controlled by a 10-microwatt electron beam means that the device offers the possibility of 50 db or more of direct power gain. Moreover, it radiates its output into a limited solid angle whereas a CRT radiates in all directions. Thus, on this count alone, if some external data plane is to be illuminated, the scanlaser is brighter than a CRT by an additional factor roughly of the order of the square of the f -number of the optical system. Although one cannot yet specify the extent of the value of the coherence of its output, one can readily visualize applications, such as scanning optical radar, where coherence would be a valuable feature.

Evidently, the key most essential to achieving a variety of practical applications of the scanlaser is the emergence of a high-gain, high-numerical aperture cw laser medium.* Toward that end, the recently reported¹⁸ high numerical aperture ion lasers appear extremely promising, as do the high-gain, high-efficiency Nd:YAG lasers that have become commercially available.

* Nonetheless, the rapidly pulsed mercury laser has interesting implications for applications not requiring a continuous light source.

Finally, we conclude that the potential utility of the scanlaser is still somewhat dependent on advances in technology but that the likelihood for achieving those advances is substantial.

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References

1. See, for example, C. J. Peters, *Proc. IEEE* **51**, 147 (1963).
2. See, for example, F. S. Chen et al., *Proc. IEEE* **52**, 1258 (1964).
3. For example, as manufactured by Beckman and Whitley, Inc., Mountain View, California.
4. W. Kulcke et al., *Appl. Opt.* **5**, 1657 (1966).
5. J. W. Crowe and R. Craig, Proceedings of the International Solid State Circuits Conference, Philadelphia, 94-95, (February 1967).
6. M. G. Cohen and E. I. Gordon, *Appl. Phys. Lett.* **5**, 181 (1964).
7. R. V. Pole, *Z. Angew. Math. und Physik* **16**, 173 (1965).
8. R. V. Pole, *J. Opt. Soc. Am.* **55**, 254 (1965).
9. (a) R. A. Myers and R. V. Pole, *J. Opt. Soc. Am.* **55**, 1574 (1965). (b) J. S. Wilczynski and R. E. Tibbetts, *ibid.*
10. D. Slepian and H. O. Pollak, *Bell Syst. Tech. J.* **40**, 43 (1961).
11. R. V. Pole et al., *Optical and Electro-Optical Information Processing* (Tippett et al., editors), M.I.T. Press, Boston (1965), pp. 351-364.
12. M. von Ardenne, U. S. Patent 2,276,359 (1939).
13. C. B. Zarowin, *Appl. Phys. Lett.* (To be published).
14. H. Wieder et al., paper submitted to *Rev. Sci. Inst.*
15. R. L. Garwin, private communication.
16. R. V. Pole and R. A. Myers, *J. Quant. Elect.* **QE-2**, 182-184 (1966).
17. R. L. Byer et al., *J. Opt. Soc. Am.* **55**, 1598 (1965).

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